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Flexible low-mass devices and mechanisms actuated by Electroactive Polymers

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ABSTRACT

Miniature, lightweight, miser actuators that operate similar to biological muscles can be used to develop robotic devices with unmatched capabilities to impact many technology areas. Electroactive polymers (EAP) offer the potential to producing such actuators and their main attractive feature is their ability to induce relatively large bending or longitudinal strain. Generally, these materials produce a relatively low force and the applications that can be considered at the current state of the art are relatively limited. This reported study is concentrating on the development of effective EAPs and the resultant enabling mechanisms employing their unique characteristics. Several EAP driven mechanisms, which emulate human hand, were developed including a gripper, manipulator arm and surface wiper. The manipulator arm was made of a composite rod with an EAP actuator consisting of a scrolled rope that is activated longitudinally by an electrostatic field. A gripper was made to serve as an end effector and it consisted of multiple bending EAP fingers for grabbing and holding such objects as rocks. An EAP surface wiper was developed to operate like a human finger and to demonstrate the potential to remove dust from optical and IR windows as well as solar cells. These EAP driven devices are taking advantage of the large actuation displacement of these materials but there is need for a significantly greater actuation force capability.

Keywords: Miniature Robotics, Electroactive Polymers, Hand Simulation, EAP Actuators, Surface Wiper, EAP Gripper

1. INTRODUCTION

Efficient miniature actuators that are light, compact and driven by low power are needed to drive telerobotic devices and space mechanisms in future NASA missions. Examples of space mechanisms and devices that require actuators include robotic arms, miniature rovers, release mechanisms, positioners, etc. Electroceramics (EAC) offer effective, compact, actuation materials and they are incorporated into such mechanisms as ultrasonic motors, inchworms, translators and manipulators. In contrast to EACs, electroactive polymers (EAP) are emerging as new actuation materials [Furukawa and Wen, 1984] with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. EAPs are lighter and their striction capability can be as high as two orders of magnitude more than EACs [Bar-Cohen, Xue, et al, 1997]. Further, their response speed is significantly higher than Shape Memory Alloys (SMAs). The authors' current study is directed towards taking advantage of these polymers' resilience, fracture toughness and the ability to engineer their properties [Hunter and Lafontaine, 1992; Kornbluh, et al, 1995; and Shahinpoor, 1994]. Generally, once their ability to induce large force is sufficiently enhanced they can be designed to emulate the operation of biological muscles. They offer unique characteristics of high toughness, large actuation strain constant and inherent vibration damping.

The development of actuators that emulate muscle is involved with interdisciplinary efforts using expertise in materials science, chemistry, electronics, and robotics. The infrastructure of this field is still lacking the key technologies and capabilities that need sufficient progress before such actuators can be used for such applications as augmenting handicap mobility. The authors identified two electroactive polymer categories of inducing large actuation strains including (a) bending actuators: Ion exchange membrane metal composites; and (b) longitudinal actuators: electrostatically activated EAPs. In parallel to the authors research effort to develop efficient materials, they are seeking to identify robotic and planetary applications in NASA future missions to transfer the technology. Recent results have shown that the bending EAP can be activated at low temperatures and vacuum, which are important requirements for operation at planetary conditions. However, this material is critically sensitive to the water content inside its porous matrix and requires effective coating to protect the material from water loss through evaporation. Another hampering issue is the electrolysis of water that takes place during its electroactivation causing degradation, heat and release of gasses. Moreover, the material induces relatively low force making it difficult to find applications where its capability is useful. Besides the design of mechanisms where the EAP actuators can be employed while accounting for their deficiencies, a study is underway to develop computer control capability for remote operation. An important issue that needs adequate attention is the current lack of effective sensors that are flexible and lightweight to provide feedback data for robotic tasks actuated by EAP materials. However, EAP materials can also act as sensors for motion and force gauging [Shahinpoor and Mojarrad, 1997]

2. IONOMERS AS BENDING EAP ACTUATORS

There are many forms of bending EAP materials, which have emerged in recent years. The authors concentrated on the use of perfluorosulfoninated ion exchange membrane metal composite films having deposited metal electrodes on both sides. The base polymer layer is Nafion®, mostly #117 (Dupont product), which in its processed form has a thickness of 0.18-mm. These materials have been used for fuel cells and production of hydrogen (hydrolysis) for a number of years and their operation as actuators is the reverse process of the charge storage mechanism. In this reported research, the authors used platinum as the metallic electrodes. However, other researchers reported a great success using such metals as gold [Yoshiko, et al, 1998]. Further, in this study the counter cation has been sodium but the authors have been well aware of the greater efficiency of using lithium as cations to induce larger displacement and force density per applied voltage. In cooperation with the Osaka National search Institute, Japan, efforts are underway to employ the gold-coated lithium cation type bending EAP. In this reported study ion exchange polymer metal composite (IMPC) was used having platinum electrodes and employing sodium ions. Once the Nafion sheet is loaded with platinum near it surface boundaries serving as the electrodes, it is cut to strips that are 25.0x3.5-mm in size and weigh 0.1-g. To maintain the actuation capability of IMPC, the material needs to be kept moist continuously providing the necessary media for ion mobility that is responsible for the actuation. Without coating the material can work in air for less than a few minutes, whereas a recent coating technology that was introduced at NASA-LaRC allowed operating the actuator for about 4 months. The required drive voltage was found to range from 1 to 5-volts at room temperature and the voltage needs to be kept as low as possible to avoid the side effect of electrolysis during activation.

When an external voltage is applied on an IPMC film, it causes bending towards the anode at a level that increases with the voltage, up until reaching saturation, as shown in Figure 1. Under AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Generally, activation at lower frequencies (down to 0.1 or 0.01 Hz) induces higher displacement. The level at which the bending reaches displacement saturation as a function of the drive voltage depends on the frequency and it is smaller at higher frequencies. The movement of the film is controlled by the applied electrical source but it is strongly affected by the water content that serves as an ion transport medium. Unfortunately, IPMC strips do not maintain the actuation displacement under a DC voltage as they retract after several seconds. Further, upon removal of the electric field an overshoot displacement occurs in the opposite direction and with a slow return to a steady state position. The operation of the IPMC as a bending actuator is demonstrated in a configuration of a window surface wiper in Figure 2, where the ionomer was driven by 2.5V to remove sawdust. As can be seen in this Figure, an actuator strip is attached to the surface of a glass plate and is actuated left or right as desired by changing the polarity of the drive voltage. Recent tests of the performance of the ionomers at low temperatures showed that while the response decrease with temperature, a sizeable displacement was still observed at -140°C. This decrease can be compensated by increase in voltage. It is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels.

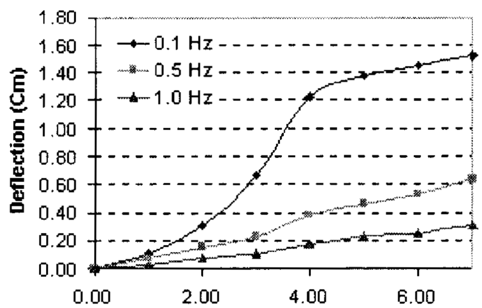

Figure 1: The response of the bending EAP to various voltage amplitudes at three different frequencies.

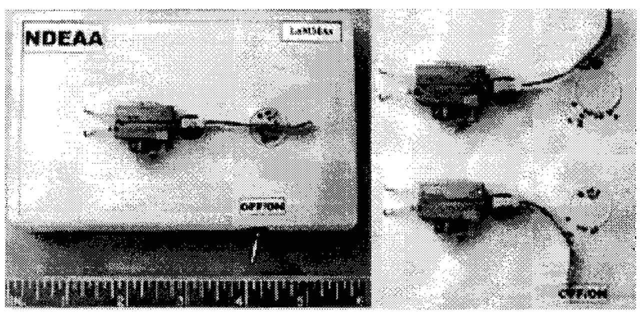

Figure 2: A view of a surface wiper with a simulated window and dust, where an EAP is bending back and forth to remove the dust.

3. LONGITUDINAL ELECTROSTATIC POLYMER ACTUATORS

Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting the material to an electrostatic field. These characteristics of polymers allow producing longitudinal actuators that operate similar to biological muscles using Coulomb forces between electrodes to squeeze or stretch the material. Traditional electrostatic actuators are fabricated as a capacitor with parallel electrodes with a thin air gap between them. Two of the major disadvantages of this type of actuators are their relatively low breakdown voltage and the fact that they produce longitudinal extension rather than contraction. The authors adopted the approach that was reported by Kornsluh, et al, 1995, where a longitudinal electrostatic actuator is made of dielectric elastomer film coated with carbon electrodes. The force (stress) that is exerted normally on such a film with compliant electrodes is as follows:

$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V / t)^2 \tag{1}$$

where: P is the normal stress, ε_0 is the permittivity of vacuum and ε, is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film.

Examining the equation above, it is easy to notice that the force magnitude is twice as large as that for the case of rigid parallel electrodes. To obtain the thickness strain the force needs to be divided by the elastic modulus of the film. Use of polymers with high dielectric constants and application of high electric fields induces large forces and strains. To obtain the required electric field levels one needs to either use high voltage and/or employ thin films. For elastomers with low elastic modulus, it is reasonable to assume a Poisson's ratio of 0.5. This means that the volume of the polymer is kept constant while the film is deformed under the applied field. As a result, the film is squeezed in the thickness direction causing expansion in the transverse plane. For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components are neglected.

$$\Delta D / D_0 = -(1/2)\Delta t / t_0 \tag{2}$$

where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and Δt is its change under electric activation.

To produce a longitudinal actuator with large actuation force, a stack of two silicone layers (Dow Corning Sylgard 186) was used with carbon electrodes on both sides of one of the layers. The displacement in the rope cross section is a rotational one around the rope axis and it is constrained by interlaminar stresses. Therefore, the total actuation extension of the rope is proportional to its length and the resultant actuation force is proportional to the cross-section area normal to the axis. To develop an EAP muscle using such a rope, the length and diameter are used as design parameters, enabling the adaptation of the rope actuator to specific applications. In Figure 3, a silicone film is shown to produce about 12% extension and in a rope form it is used to drop and lift a 10-g rock with displacement of about 6%. This actuation strain level was obtained at about 2000-V.

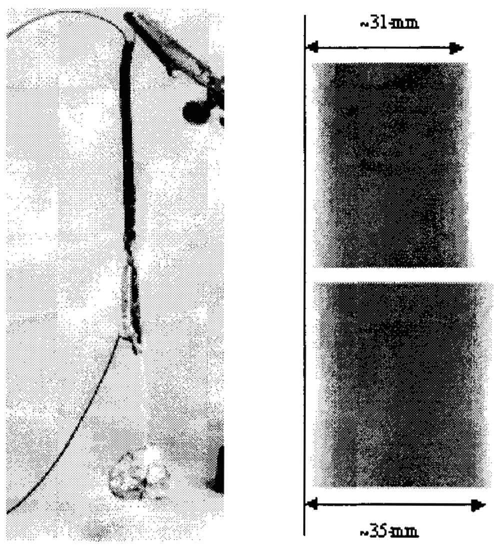

Figure 3: Using an electroded silicone film a 12% extension was obtained by electro-activation (right) and in a rope shape the actuator is shown lifting 10.3-g rock (left)

4. ROBOTIC APPLICATIONS USING EAP ACTUATOR

The availability of EAP actuators that can bend or extend/contract capable of producing unique robotic devices that emulates human hands. The authors investigated several potential applications including robotic arm, gripper, surface wiper and a rake. A robotic arm was developed and programmed for computer control as shown in Figure 4.

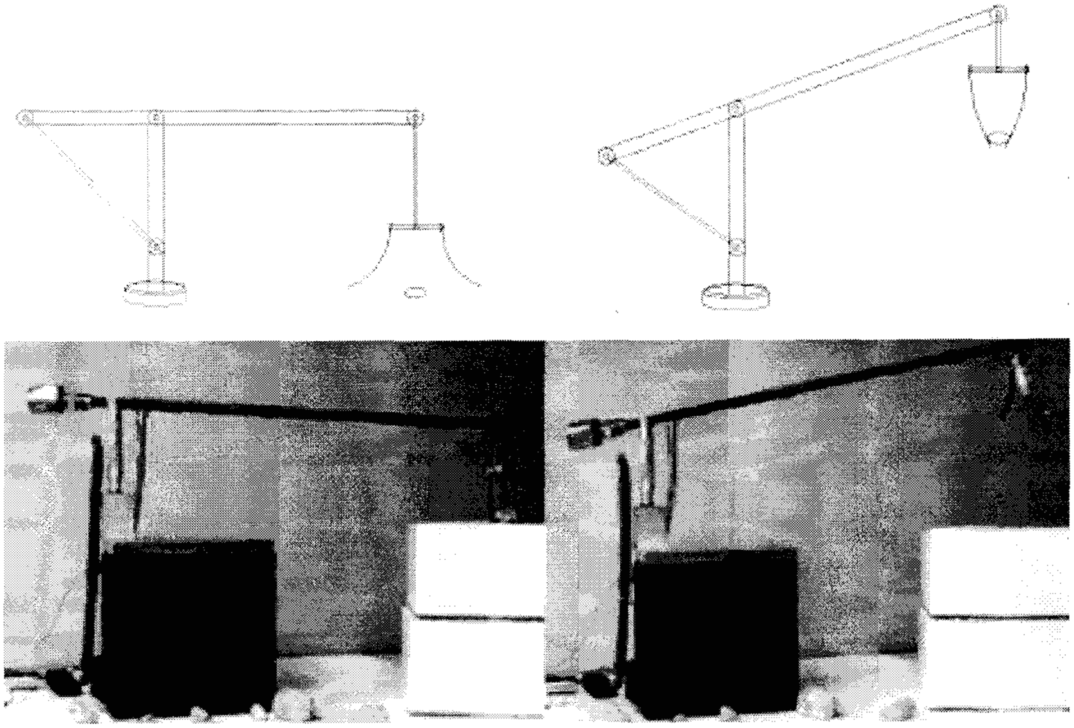

Figure 4: A simulated view (top) and a constructed robotic arm, which takes advantage of the capability of longitudinal and bending EAP actuators.

To form a miniature lightweight robotic arm a 5-mm diameter graphite/epoxy rod was used and a rope was connected on the short end of this balanced rod and was used to lower and raise the arm as shown in Figure 4. On the right of the rod a gripper was mounted as an end effector using bending EAP fingers and miniature hooks to secure the gripped objects. The rope consisted of a silicone film and it required voltage levels of 30-70 V/μm, which reached between 1000 and 2500-Volts to produce the levels of several percents actuation strain (shown in Figure 3). Since the film is squeezed as a result of the activation, it becomes longer under the electro activation making the rope longer. This longitudinal EAP rope actuated the arm by tilting its balance and the lifting displacement is determined by the ratio between its connection distance from the pivot point compared to the gripper distance. The longitudinal EAP was used here as the equivalent of human muscle with the exception that it becomes longer under activation. The gripper having fingers to grab and hold objects formed the equivalent to human hand. The inability of the bending EAP to lift any significant mass was taken into account in this application by avoiding this necessity. The fingers, which have remarkable opening capability, were used to "hug" the samples and grab them by hooks that were attached at the finger ends. The fingers move back and forth opening and closing the gripper similar to a human hand, embracing the desired object and gripping it. The hooks at the end of the fingers function similar to fingernails to hold the object securely. The gripper was driven by 2 to 5-V square wave signal at a frequency of 0.1-Hz to allow sufficient time to perform a demonstration of the gripper capability. The robotic arm was programmed such that it is lowered near the object to be collected, the gripper fingers are opened as the arm comes down and allowed to close on the object and hold it with the aid of the hooks. To drive the arm, voltages at the level of about 2-KV was used. At this point the fingers are closed and the object is lifted. The demonstration of this robotic arm and gripper capability to lift a rock was intended to pave the way for a future application to planetary sample collection tasks providing miniature ultra-dexterous and versatile tool.

Lessons learned from Viking and Mars Pathfinder missions indicate that the operation on Mars involves with an environment that causes the accumulation of dust on the hardware surfaces. The dust accumulation is a critical problem that hampers long-term operation of optical instruments and degrades the produced power efficiency of solar cells. To remove dust from surfaces one can use a similar mechanism like automobile windshield wipers. Unfortunately, conventional surface wiping mechanisms are cumbersome, heavy, power intensive and cannot be practical for such tasks as dust removal from individual solar cells. Contrary to conventional actuators, the bending EAP has the ideal characteristics that are necessary to produce surface wipers. As shown earlier in Figure 2, a simple, miniature, lightweight, low power surface wiper can be constructed using an IPMC film. The ionomer responds to activation signals at the .3-Hz range and the angle of bending can exceed 90 degrees span each way while covering 25-40 mm radius using about 40-50 mm long wiper. The wiper element can be placed straight in the middle of the desired area and activated to sweep left and right by switching the electric field polarity. Also, it can be located on the side of the desired area and activated in one direction. The dust removal capability of the bending films addressed a critical NASA problem and a pair of surface wipers is currently being designed for use on the miniature JPL rover called Nanorover. This rover is constructed for the mission MUSES-CN to an asteroid using a Japanese rocket and the launch is expected in 2002. A cooperative effort with the Osaka Research Institute is currently underway to potentially employ their bending EAP material in this mission.

5. CONCLUSION

Two types of electroactive polymer actuators, which induce large displacement actuation, were employed in this study to develop components of a robotic arm that emulated human hands and a dust-wiper. While the material performance is being enhanced, methods of controlling the actuation performance are being investigated. The ion-exchange EAP offers a large bending actuation and allows emulation of the dexterity of human hand and fingers using lightweight low power material. For longitudinal displacement actuation, electrostatically activated films were rolled to form ropes and to serve equivalently to biological muscles. These electroactive polymers are showing a superior actuation displacement, mass, cost, power consumption and fatigue characteristics over conventional electromagnetic, EAC and SMA actuators. While the force actuation capability of EAPs is limited, their actuation displacement levels are unmatched. Telerobotic devices were constructed using EAPs enabling the actuation of unique mechanisms. A multi-fingered gripper was demonstrated to have large finger opening and closing capability with a relatively large mass carrying capability. A miniature robotic arm was constructed similar to human hand using a composite rod and a scrolled rope electrostatic actuator for the lifting mechanism and a 4-finger gripper as an end-effector. Currently, the practical application of IPMC bending-EAP is constrained by the need to prevent the film from drying and losing its ionic constituents and the introduction of electrolysis. To address the issue of dust during planetary exploration such as Mars and asteroids, a unique dust wiper is currently being developed to become a flight-qualified device. Generally, this EAP development effort has changed the paradigm about the construction of robots. Robotic mechanisms can now be constructed which don't involve any conventional components like motors, gears, bearings, screws, etc. In spite of the great success that was demonstrated the infrastructure of EAPs still lacks key technologies and the research community is challenged to bring the force capability of these materials to the level that can arm wrestle with human and win.

6. ACKNOWLEDGEMENT

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